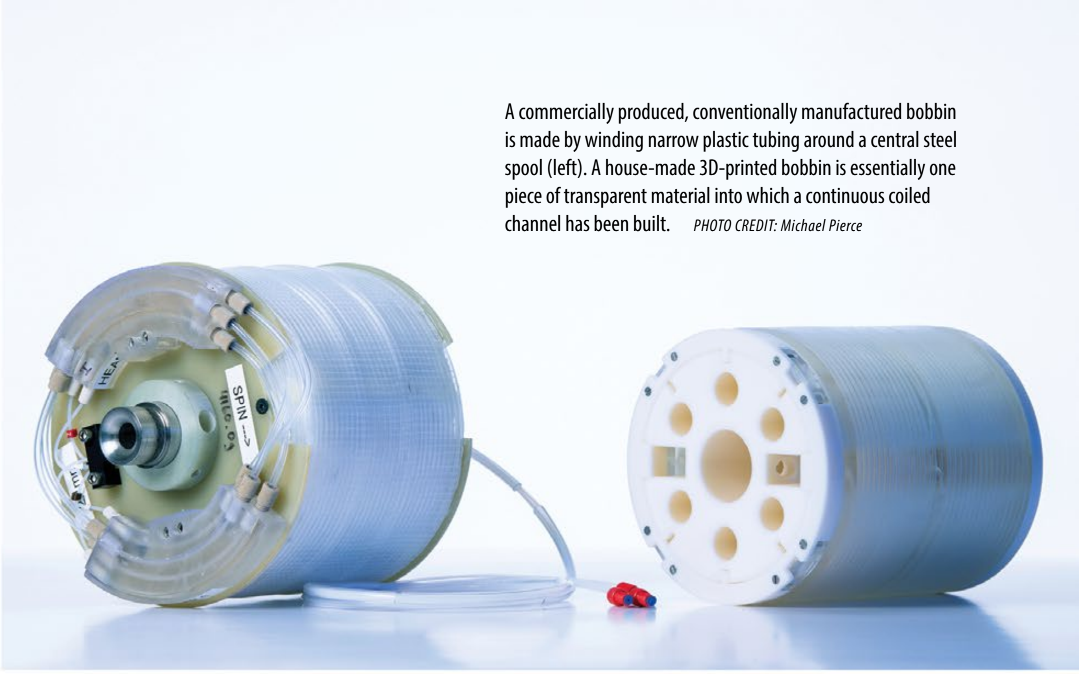
RESOURCE REVOLUTIONS

3D PRINTING HELPS CONSERVE RESOURCES AND REDUCE WASTE IN SERVICE OF THE LABORATORY'S PIT-PRODUCTION GOAL

PHOTO CREDIT: Michael Pierce

WHEN THEIR BOBBIN BROKE on day one, George Goff and Kevin Boland knew there had to be a better way. It had been an expensive bobbin—both moneywise and timewise, having been custom ordered and several months in the waiting—and it broke right out of the gate. The two scientists, in need of a bobbin for plutonium purification, decided that if they could make their own bobbins in house, they could duck the cost, skirt the wait, and likely improve recycling of plutonium and other radioactive materials at the Lab.

Working with plutonium is similar, in some ways, to working with other metals in that it involves melting, casting, machining, and welding. But plutonium is quite different from most metals—it undergoes radioactive decay, has unexpectedly weak magnetism, expands and contracts more than other metals, and increases in density, rather than decreasing, when it melts. These traits make plutonium metallurgy particularly complicated and difficult. To keep the workers safe and the material secure, plutonium facilities are extraordinarily specialized and astonishingly expensive to build.



A commercially produced, conventionally manufactured bobbin is made by winding narrow plastic tubing around a central steel spool (left). A house-made 3D-printed bobbin is essentially one piece of transparent material into which a continuous coiled channel has been built. *PHOTO CREDIT: Michael Pierce*

Los Alamos is the National Nuclear Security Administration's Center of Excellence for Plutonium Research and Development. As such, it is one of the national laboratories that has been charged with scaling up the production of pits—the plutonium cores used in nuclear weapons—to 80 per year by 2030, in support of the nation's strategic nuclear deterrent. In order to meet this mission goal, Laboratory scientists are looking for creative new ways to reduce, reuse, and recycle within the pit-production process. Costs can be cut by reducing the footprint of these chemical processes within the facility, by reusing as much plutonium as possible, and by recycling key materials to minimize waste and maybe generate a bit of revenue to offset costs.

But first, back to the busted bobbin.

Reduce

The bobbin that broke was roughly the size and shape of a coffee can and consisted of dozens of meters of narrow plastic tubing coiled around a central spool. The bobbin is the business end of a machine called the coil planet centrifuge, which uses centrifugal force for chromatography—the physical separation of particles in a suspension through which different particles travel at different speeds.

The coil planet centrifuge does high-speed counter-current chromatography (HSCCC) and was originally developed to separate different kinds of blood cells (e.g., lymphocytes, granulocytes, erythrocytes) in a blood sample. The technique is called "counter-current" because of how two immiscible liquids interact within the bobbin as it spins. The two liquids, an organic phase like oil and an aqueous phase like water, occupy the bobbin's plastic tubing as the bobbin spins around. One of the liquids is held in place (not flowing into or out of the bobbin) by centrifugal forces, while the second phase flows through the bobbin, moving past the immobile phase within the plastic tubing. Due to the high rotational speeds, the result of this counter-current chromatography is the fast and efficient transfer of molecules from one phase to the other.

HSCCC is used for all manner of separations, ranging from herbal medicine preparation to weapons-grade plutonium purification. Goff and Boland were pursuing the latter of these as part of a larger plutonium-separation project led by Laboratory engineers Steve Yarbro and Brad Skidmore. The team decided they needed a 3D-printing expert, so they brought in chemical engineer Alex Marchi to help with the bobbin problem.

Initially, the scientists bought a commercial coil planet centrifuge to study HSCCC as a reduced-footprint method for purifying plutonium. If the machine could be accommodated inside a glovebox—a fully sealed glass and steel workstation where radioactive materials are handled—it could free thousands of square feet of invaluable facility space for other types of processing. But there were a lot of problems adapting the commercial unit to work inside a glovebox, not least among which was the bobbin. Made mostly of steel, the centrifuge pieces are heavy to lift and clumsy to maneuver within the glovebox, and they are easily damaged by some of the chemicals used in plutonium processing. The opacity of the system was also problematic.

Marchi explains, "We want to understand the hydrodynamics and chemistry of separation within the commercial unit, but it is literally a black box—all the moving parts are encased in a steel housing. I want to be able to see what's happening."

COSTS CAN BE CUT BY REDUCING THE FOOTPRINT OF CERTAIN CHEMICAL PROCESSES WITHIN PLUTONIUM FACILITIES

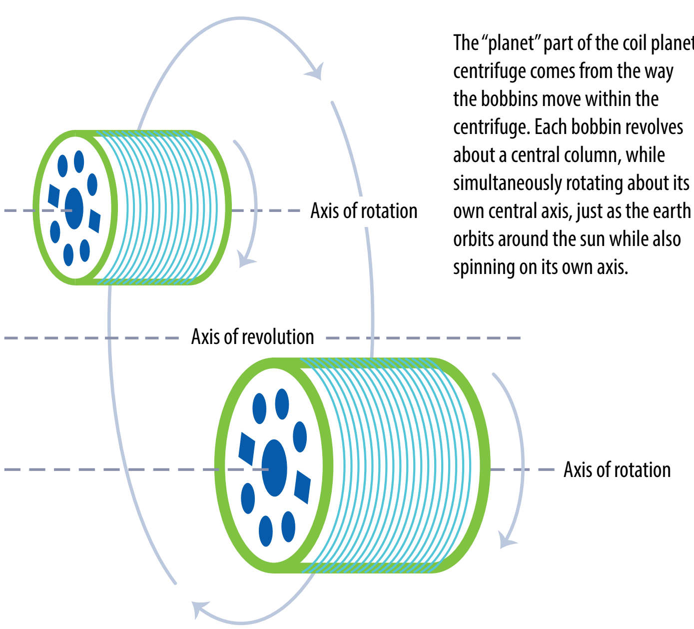
Marchi and Goff explored 3D printing as a way to build a better bobbin. A form of additive manufacturing, 3D printing deposits layer upon layer of material—usually some sort of plastic or resin—until a single, solid object has been formed. The technology is particularly useful for making items with intricate internal spaces and proved ideal for bobbin building.

The in-house 3D-printed bobbins Marchi and Goff designed can be manufactured in just four days, compared to six months for the commercial ones. They also cost about 85 percent less.

And these bobbins are indeed better—they are optically transparent, very lightweight, and resistant to strong acids, organic solvents, and radiation damage. And because each is one solid piece there are fewer points of failure. In fact, the only failures the team has seen so far have been post-production machining mishaps. But because of the short manufacturing timeline and comfortable cost, when over-eager threading and tapping of the ports causes a bobbin to crack, it's easy enough to make a new one.

As the team worked with the commercial centrifuge in pursuit of the best bobbin designs, Goff and Marchi realized 3D printing could improve more than just the bobbin. Conventional machining imposes certain constraints on design; what gets built is whichever design is most practical from a manufacturing perspective, not necessarily the design that will do the best job. For example, a 90-degree bend is not ideal for fluid flow, but using more gradual bends means using more parts, which drives up the cost of manufacturing. With 3D printing that is no longer true, so Marchi got creative, incorporating smoother curves in her design, which reduced flow disruption and enabled higher-efficiency separation at no added cost. Marchi has redesigned every single part and is now printing bobbins, spindles, clips, clamps, gears, and manifolds, improving functionality and cutting cost at every turn.

ABOUT 80 PERCENT OF THE RECOVERABLE MATERIAL IS CONTAINED IN 20 PERCENT OF THE WASTE PRODUCTS



The "planet" part of the coil planet centrifuge comes from the way the bobbins move within the centrifuge. Each bobbin revolves about a central column, while simultaneously rotating about its own central axis, just as the earth orbits around the sun while also spinning on its own axis.

Reuse

Plutonium is a manmade material that is produced by bombarding uranium with neutrons. Throughout the Cold War, plutonium recycling was driven by the cost of production—it was cheaper to recover it from waste than to make more. These days, recycling is still imperative, but it is now driven by the desire to limit the amount of nuclear waste being sent to geologic disposal repositories.

The scaled-up pit-production mission at Los Alamos, or plutonium sustainment, means that maximum plutonium recovery is more important than ever. There are multiple types of material from which recovery is necessary: each step of making a pit—casting, machining, and welding—produces waste in the form of residues, filings, and slag. These get dissolved into an acid solution, which is then processed chemically to recover usable plutonium.

Traditionally, aqueous recovery of plutonium entails multiple separation and purification steps that produce a large volume of hazardous, radioactive liquid material. Not only would HSCCC reduce the facility footprint of these processes, it would improve recovery and reduce waste as well.

HSCCC uses the hydrodynamic behavior of two immiscible liquids to efficiently extract small quantities of sample from a large volume of liquid. The bobbins of the centrifuge travel in two ways: they rotate around their own central axes at around 1600 rpm, and while they're doing that, they also revolve opposite one another like planets around a shaft in the center of the centrifuge. The combined force, around 200 times the force of gravity, allows the coil channel of the bobbin to retain the stationary phase (not unlike the amusement park ride called the Gravitron), while the mobile phase gets forced through with a pump. The rapid motion causes the two phases to mix quickly and thoroughly within the channel, maximizing the rate of molecular exchange between the two phases. The result is highly efficient mass transfer: the small amount of plutonium that was in the mobile phase winds up in the stationary phase, while the mobile phase moves out the other end, taking contaminants with it.

The recovered and purified plutonium gets reused. But what happens to the contaminants?

Recycle

About 80 percent of the recoverable plutonium is contained in 20 percent of the pit-production waste products. If these products, mainly chloride salt residues, were all sent to waste repositories, they would amount to many drums and dollars worth of unnecessary waste. So, recovery is a cost-saving twofer: it rescues reusable plutonium and eliminates the lion's share of the radioactivity in the waste.

Another radioactive manmade element driving the disposal-drum count is americium. Americium is the main contaminant that accumulates in weapons-grade plutonium as it ages. When plutonium is produced in a nuclear reactor, some of the product takes the form of plutonium-241, which naturally decays into americium-241 through the release of a beta particle (a high-energy electron). Naturally, the older the plutonium is, the more americium has accumulated, so for plutonium sustainment the americium has to be removed, and HSCCC is a fast and effective way of separating the two. In the past, separated americium was indeed relegated to waste repositories, but several new technologies can make good use of it, so it now gets recycled at the Laboratory as a resource in its own right.

When an alpha particle (made of two protons and two neutrons) emitted by a highly radioactive americium nucleus interacts with a beryllium nucleus, the beryllium nucleus releases fast neutrons. It turns out that this combination, americium and beryllium, makes a neutron source that is useful to scientists, farmers, land developers, and, especially, oil and gas prospectors. The americium-beryllium neutron probe is a reliable way to measure the quantity of water in the soil. When fast neutrons from the probe collide with the hydrogen of water molecules in the ground, the neutrons lose much of their energy, returning to the probe as slow neutrons. The proportion of fast neutrons going out to slow neutrons coming back helps estimate the water content of the soil. A similar effect helps energy explorers determine where and how to drill for oil and gas.

Other potential uses of americium as a commodity rather than contaminant include neutron radiography, a nondestructive imaging technique for materials science; radioisotope thermo-electric generators, which provide power to unmanned remote facilities and spacecraft; and, perhaps most palpable, home and hearth protection via domestic smoke detectors. Alpha particles released from a small amount of americium ionize the air inside the detector, causing a flow of ions between two electrically charged plates. Smoke particulates entering the detector absorb the alpha particles and disrupt the flow of ions, which triggers the alarm.

By improving recovery of both plutonium and americium, pit-production waste streams can be trimmed and costs offset.

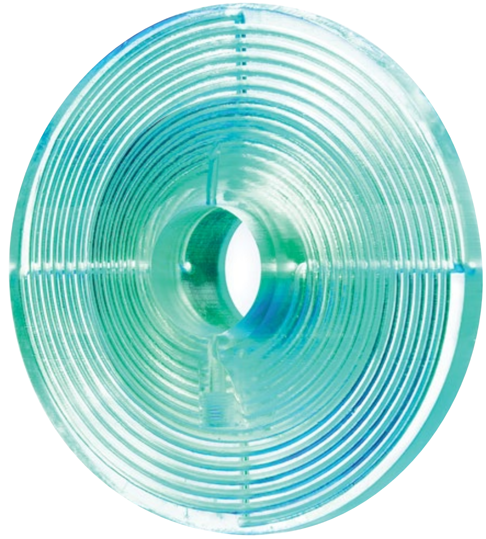
Revenue

This project will significantly reduce the footprint of chemical processing in the Laboratory's plutonium facility. It will improve how plutonium gets reused and help recycle erstwhile contaminants into the marketplace, creating a revenue stream and reducing radioactive waste.

One challenge that Marchi, Yarbro, and Goff are tackling now, which could yield significant returns outside of the Lab's national security purview, is to demonstrate how 3D-printed HSCCC could be useful for other industries.

"Plutonium processing is necessarily a batch process," says Yarbro. "Material control and accountability, as well as criticality safety, will always require it to be done in batches. But continuous processing can be useful for other industries. So, we will develop those designs too."

One notable area where HSCCC shows promise is the recovery of rare-earth elements from fly ash, a byproduct of coal combustion. Rare-earth elements, which are used in all manner of modern tech, including hybrid cars, portable electronics, and those handy little super strong magnets can be, yes, rare, but they can also be expensive. Fly ash is typically placed in landfills or stored indefinitely by powerplants. This seems shortsighted, and scaled-up HSCCC could be a productive solution.



3D-printed bobbins can be made in different shapes and sizes for different applications. Here, the transparent spiral containing the fluid channels was built by stereolithography, which uses ultraviolet light to crosslink liquid polymers into a solid. The spiral design contrasts with the helical design on pages 18–19 by inducing a sharper gradient in the centrifugal forces over a shorter path length as the fluid spirals outward.

PHOTO CREDIT: Michael Pierce

An even more consequential problem that HSCCC might solve is water desalination. As an alternative to reverse osmosis, methods are being developed to chemically extract purified water and leave the salt behind. HSCCC could be used to implement this chemistry and enable a significant reduction in the energy required; so far, the technique appears promising. With scaling and continuous processing—significant challenges for desalination—HSCCC could be useful for agriculture or even the production of drinking water.

The cost-saving opportunities afforded the Laboratory by 3D-printed HSCCC devices are various and sundry. The pit-production process itself would benefit from faster and more efficient plutonium recovery, cheaper and more versatile machines, smaller facility footprints, and fewer drums of waste. From a broader perspective, the recovery of other profitable resources like americium and rare-earth elements can raise revenue streams where previously only waste streams ran.

And it all started with that broken bobbin. LDRD

—Eleanor Hutterer

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